A *Chandra* and XMM-*Newton* X-Ray Spectral Analysis of the Core of Centaurus A

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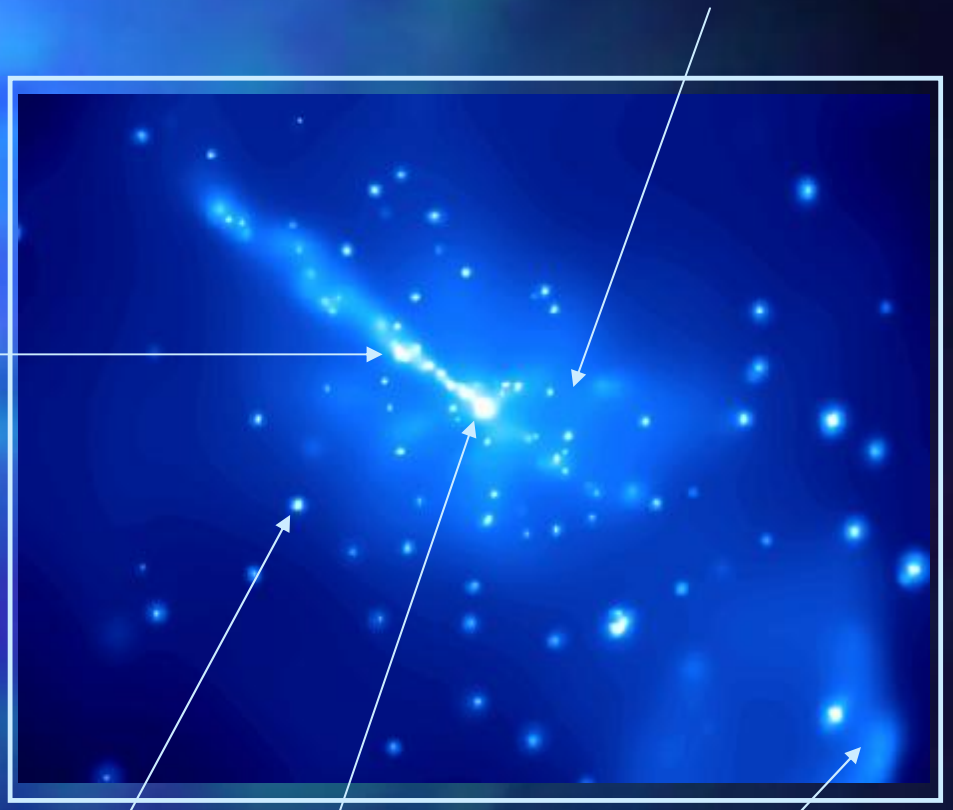
Outline

- Continuum spectrum
  - Hard power-law consistent with previous observations
  - Additional power-law consistent with VLBI jet
- Fluorescent lines
  - Resolve Fe Kα; detect Si
- Variability
  - Hard PL continuum varies over several months
  - No small (1000 s) variability
- Geometry of emission region
  - Fe Kα strength consistent with observed column

Cen A Overview

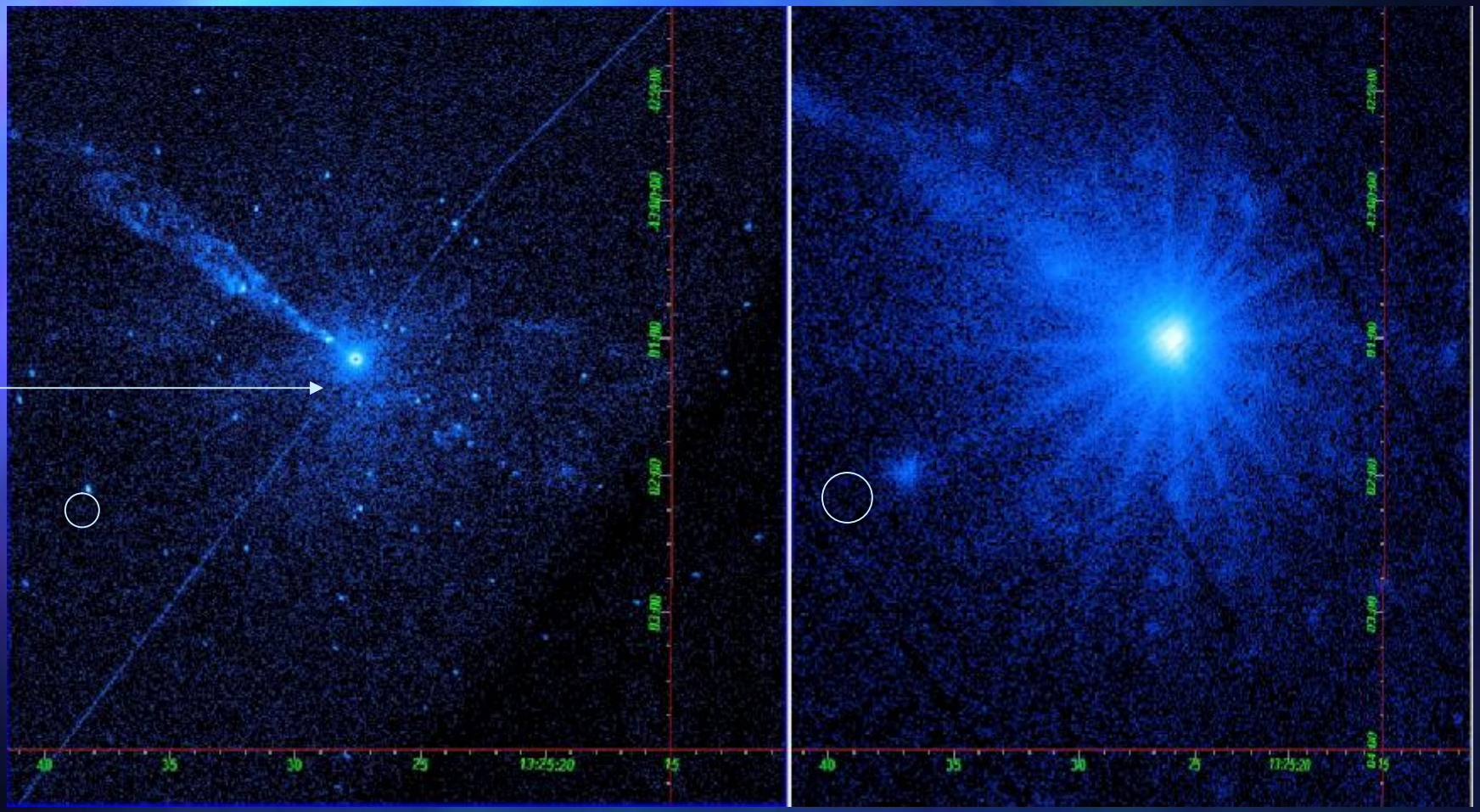
- Brightest extragalactic object in the hard X-ray sky
- Closest radio galaxy (d = 3.4 Mpc)
- Complex emission
- Ideal object to study
- Much-studied by earlier X-ray missions
- Rich gallery of radio features (jet, lobes, etc.)



Observations

- *Chandra*:
  - 2 x ~ 48 ks (May 2001) separated by 12 days using HETGS
  - Three ACIS-I/S observations without gratings (Dec 1999, May 2000, Sep 2002)
- XMM-*Newton*:
  - ~ 23 ks (Feb 2001) and ~ 13 ks (Feb 2002) using EPIC CCD instrument (MOS1, MOS2, pn cameras)
- Core pile-up
  - *Chandra* ACIS non-grating image of the core heavily piled-up
  - XMM-*Newton* EPIC piled-up but use 20" – 50" annular extraction region

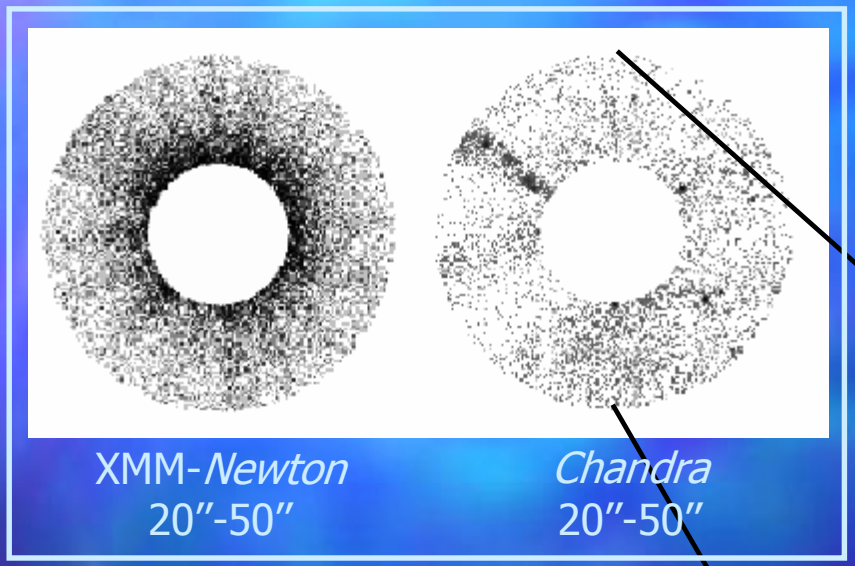
Observations

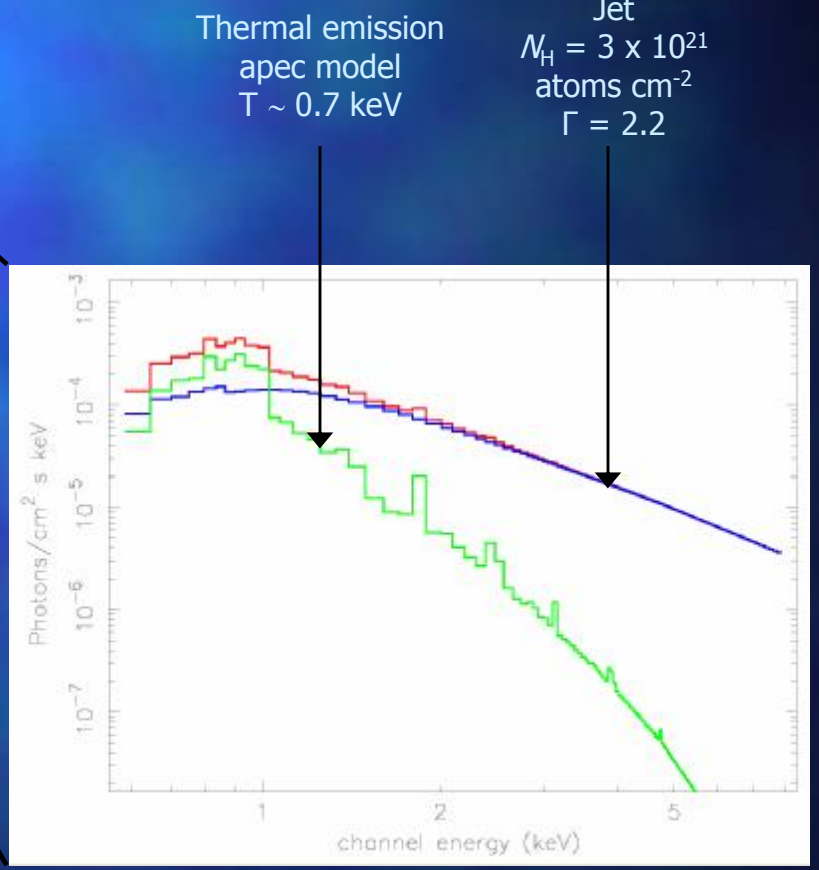


Chandra ACIS-S image (0.5–8 keV)

XMM-*Newton* (Obs. 1) MOS1, MOS2, pn combined image (0.5-10 keV)

Observations

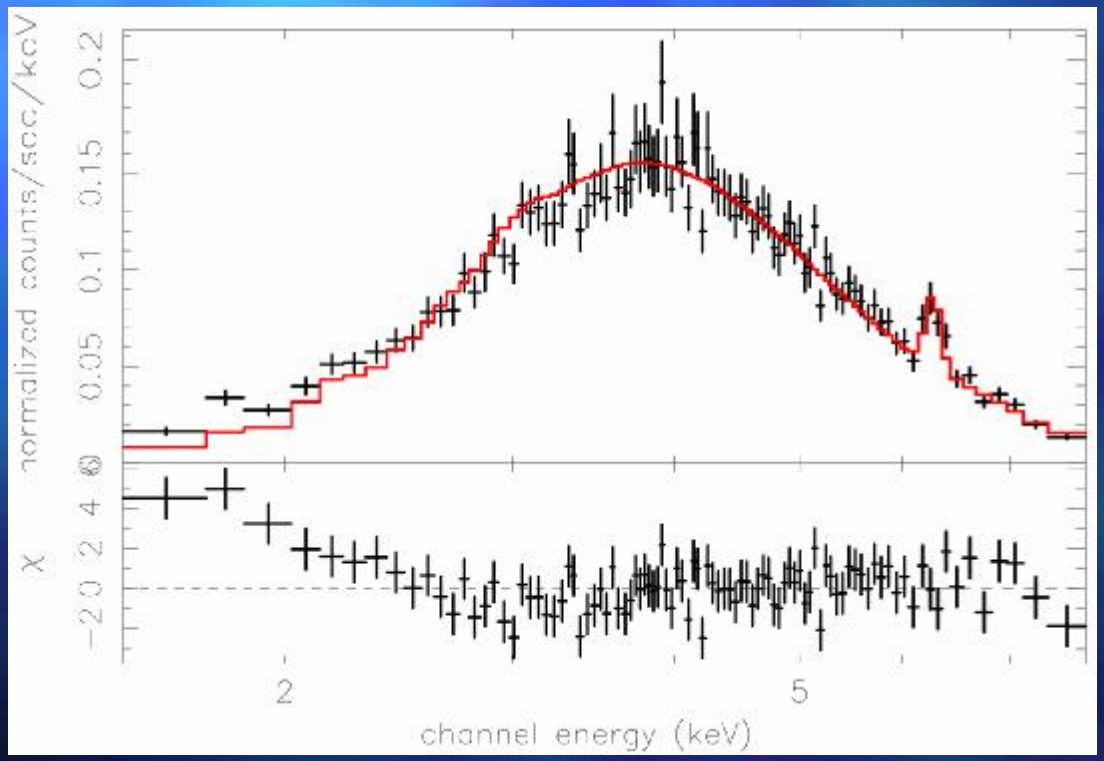




- Model diffuse components in XMM-*Newton* annulus using *Chandra* ACIS observations

Continuum Spectrum

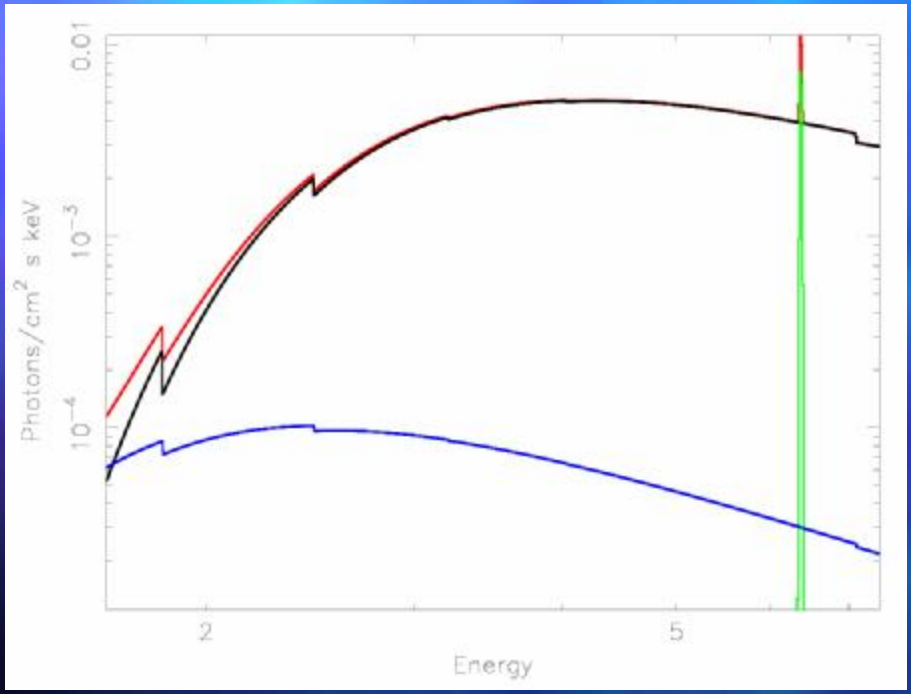
- Attempt to fit a heavily-absorbed ($N_H \sim 10^{23}$ atoms cm^{-2}) power-law ($\Gamma \sim 1.7$)
- Significant residuals below ~ 2.5 keV



XMM-*Newton* MOS2 1st observation

Continuum Spectrum

- Significant improvement (> 99% on an F-test) with the addition of a second power-law component



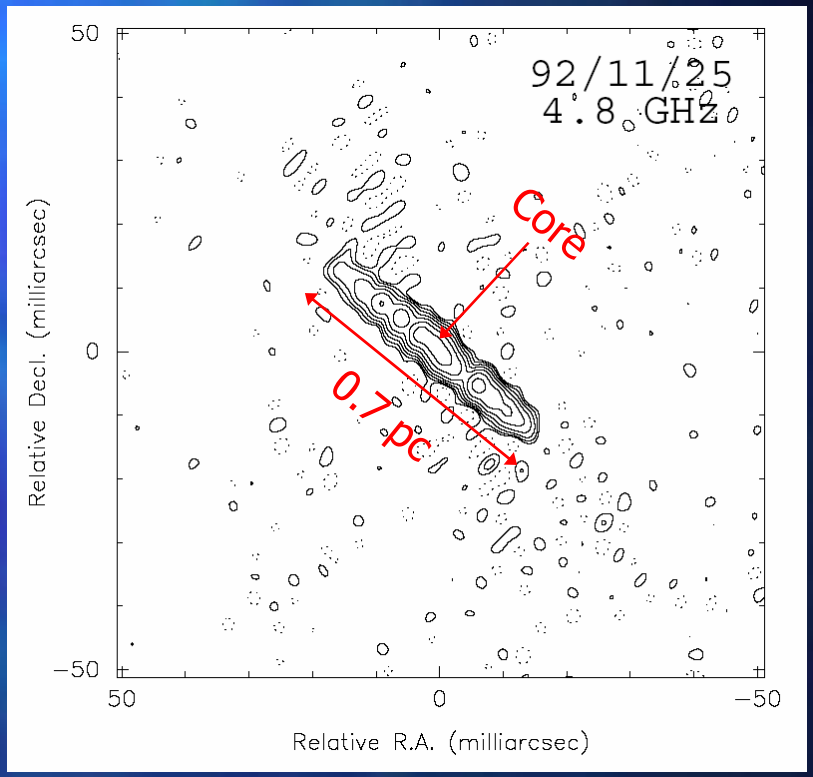
Key parameters:

Component	N_H (atoms cm^{-2})	Γ
Hard PL	(10.04 ± 1.22) x 10^{22}	1.64 ± 0.11
Soft PL	(3.1 ± 0.6) x 10^{22}	1.99 ± 0.51

- Hard PL parameters consistent with e.g. *RXTE*, *ASCA*, *BeppoSAX*

Possible Origin of 2nd PL

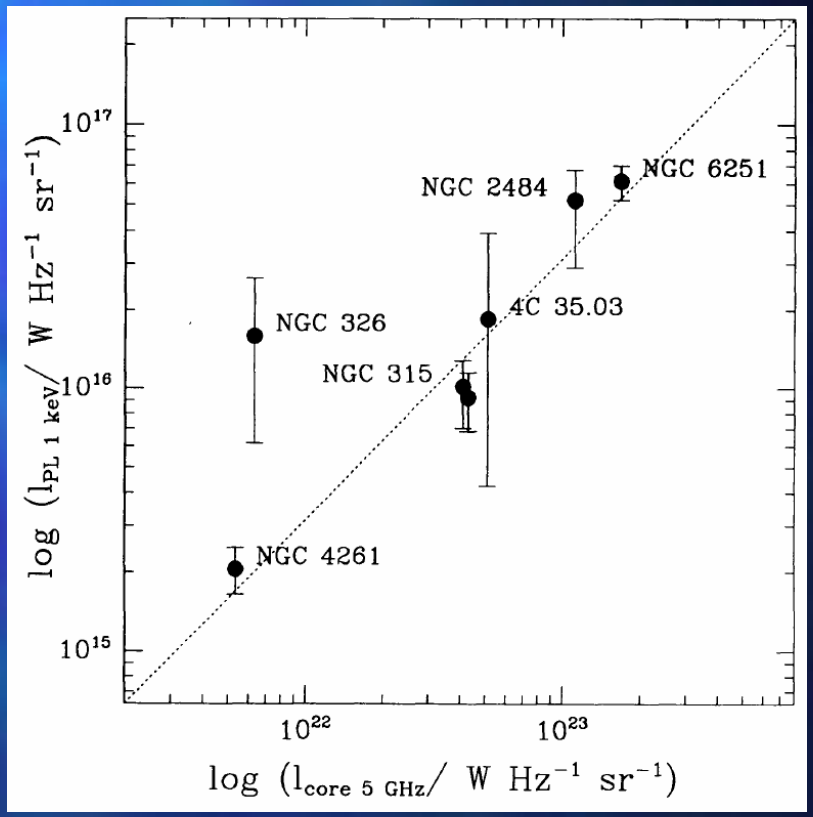
- Luminosity of 10^{39} erg s^{-1} $\Rightarrow$ highly unlikely to have kpc-scale jet origin
- VLBI jet? Flux density ~ few Jy at 4.8 GHz
- X-ray to radio ratio for 2nd PL and VLBI jet consistent with that of kpc-scale jet and VLA jet
- Investigating physical origin: SSC? IC? Synchrotron?



Taken from Tingay *et al.* (1998)

Possible Origin of 2nd PL

- VLBI variability of x3
- An explanation for single PL N_H variability seen in RXTE
- Mildly absorbed low energy power-law seen in other FRI galaxies with ROSAT



Taken from Worrall & Birkinshaw (1994)

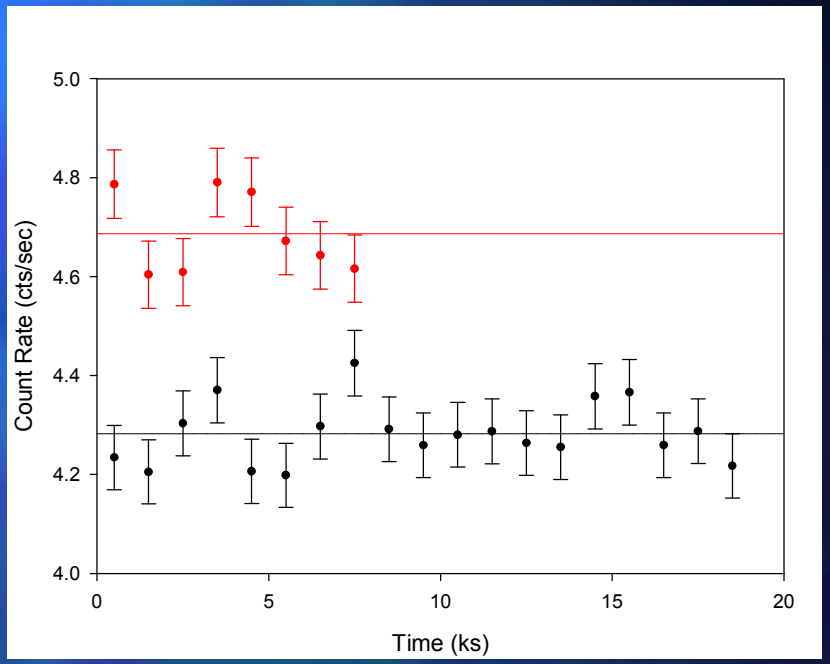
Hard Continuum Variability

- Inter-observation

Observation	4-8 keV absorbed/ unabsorbed flux (ergs s^{-1} cm^{-2})
XMM-*Newton* 1st Feb 2001	1.0×10^{-11} 1.3×10^{-11}
Chandra HEG+1 May 2001	9.0×10^{-12} 1.2×10^{-11}
XMM-*Newton* 2nd Feb 2002	1.1×10^{-11} 1.4×10^{-11}

- ~ 20% variability detected (consistent with previous observations) on timescales of months

- Intra-observation
  - 500-5000 sec time bins tried

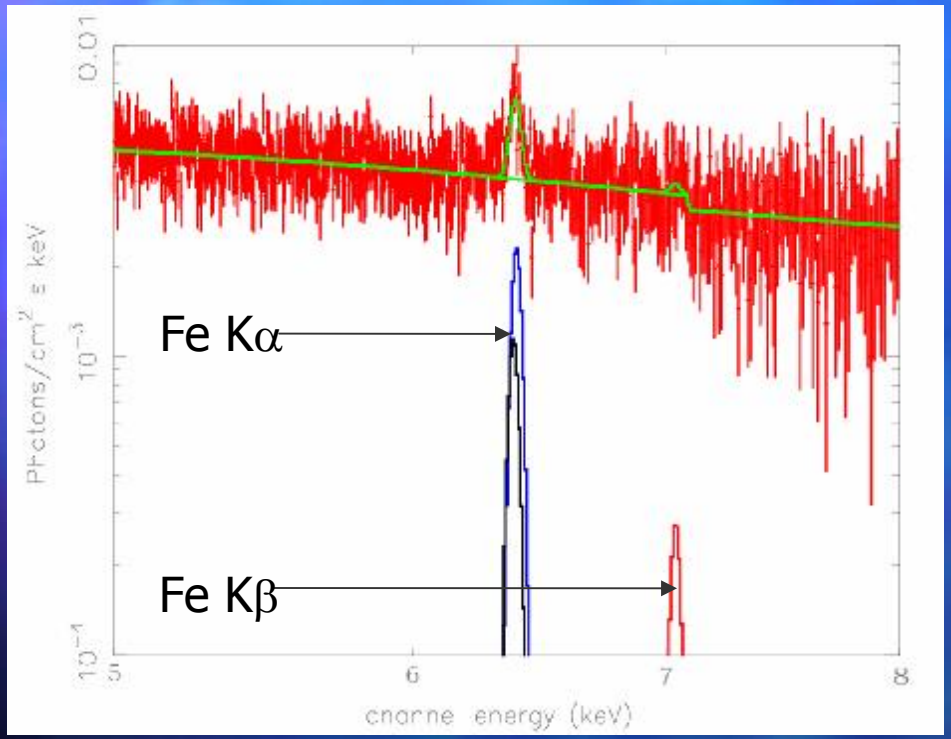


XMM-*Newton* pn, both observations, 1000 sec bins

- Consistent with no variability

Fluorescent Line Emission

- *Chandra* HETGS instrument of choice due to its high spectral resolution

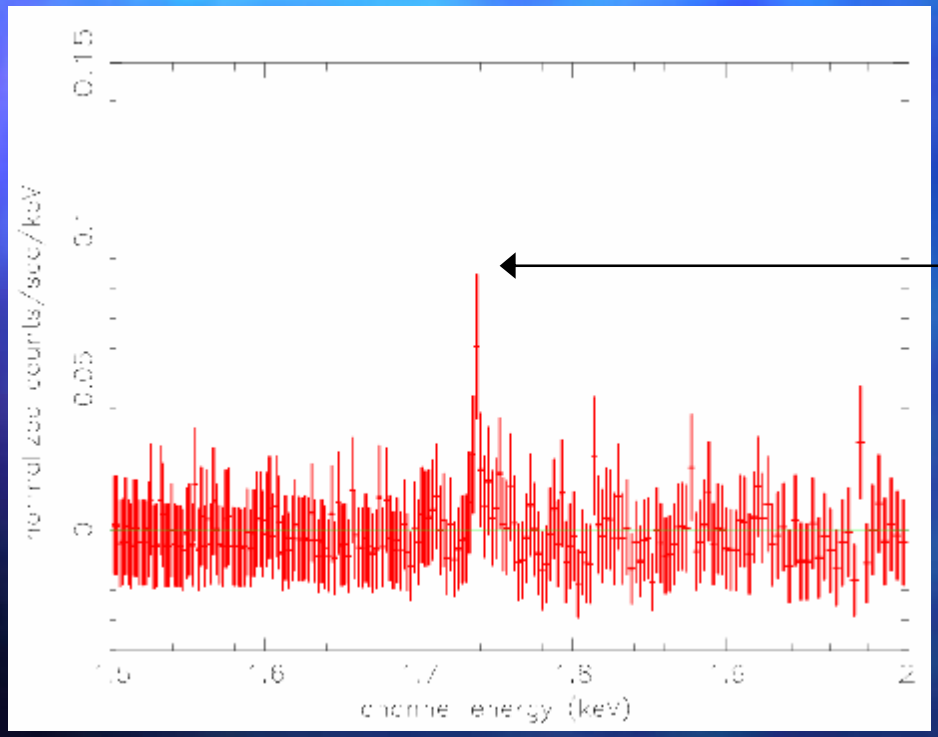


Joint HEG+1 and HEG-1 spectrum

- Fe $K\alpha_1$ centroid = 6.404±0.002 keV (90% c.l.)) ⇒ fluorescence from cold, neutral material
- Fe Kα is broadened (σ = 20±10 eV (90% c.l.)) ⇒ v ~ 1000 km s^{-1} ⇒ r ~ 0.1 pc (M_{BH} = 3 x 10^7 M_{SUN})
- Fe Kα eq. width ~ 80 eV (consistent with e.g. *ASCA*)
- 6.8 keV "ionized" Fe line claimed by *BeppoSAX* in Grandi *et al.* (2003) >> our 3σ upper limit

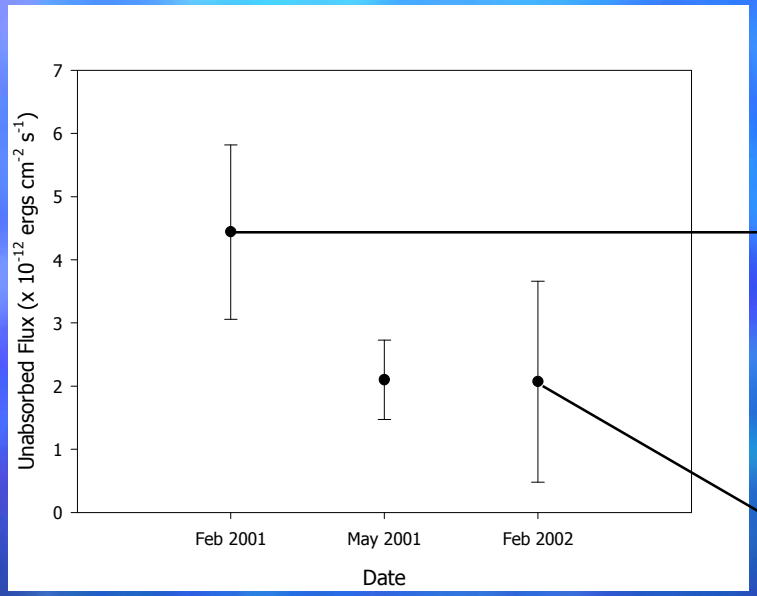
Fluorescent Line Emission

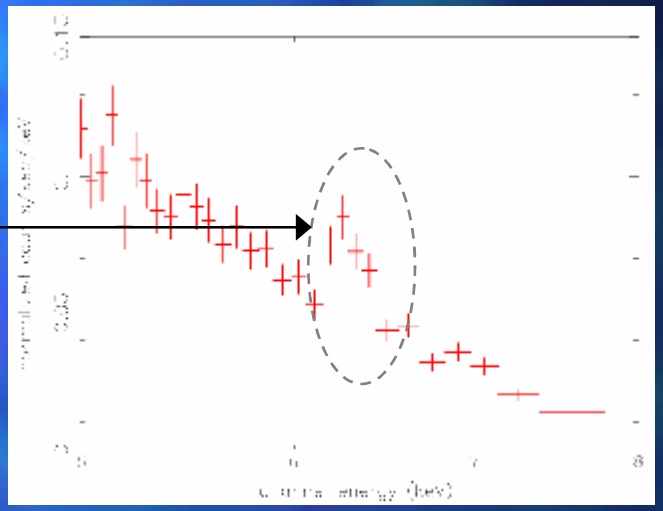
- Use MEG data to search for:
  - Emission lines (e.g. Si, S, Ca)
  - Absorption features



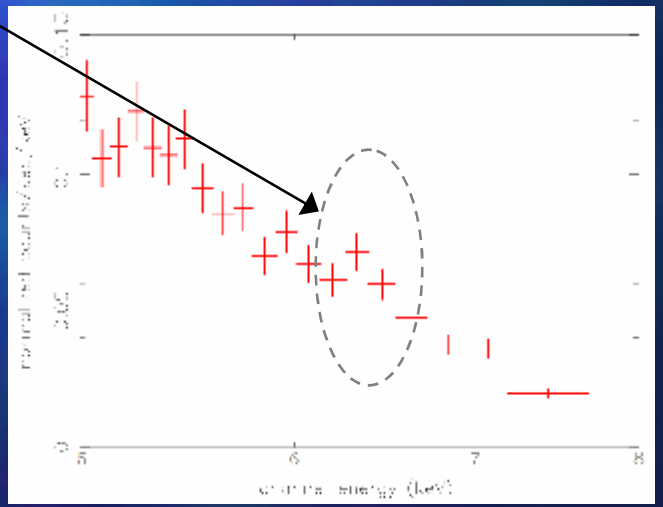
- Unresolved emission from neutral Si (1.74 keV) detected
- Eq. width ~ 38 eV, entirely consistent with ASCA
- No other features found conclusively

Fe Kα Variability





XMM-*Newton* Obs. 1



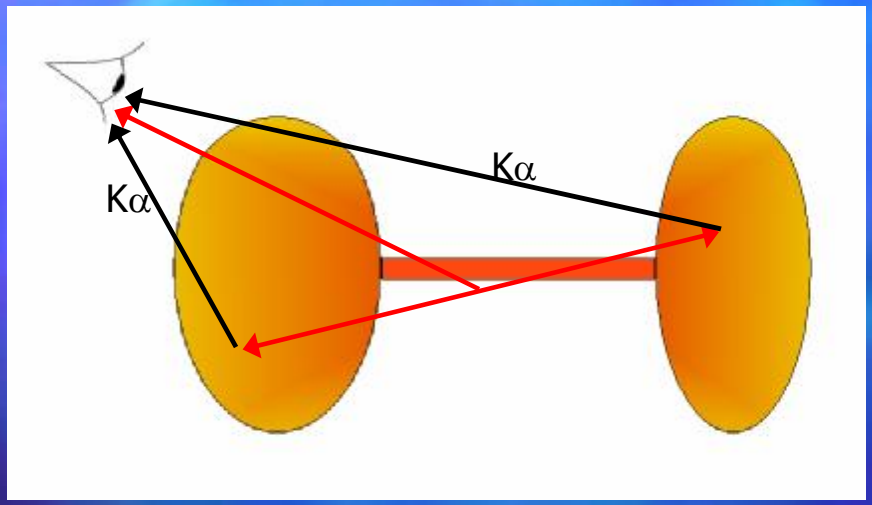
XMM-*Newton* Obs. 2

- Formally consistent with no variability
- If any variability present then on timescales of months

Geometry Of Emission Region

- Fe Kα ~ 80 eV equivalent width consistent with fluorescence from $N_H \sim 10^{23}$ atoms cm^{-2} that completely surrounds the nucleus (Miyazaki *et al.* 1996)
- Possibly a thick disk?

Geometry Of Emission Region



- Also consistent with fluorescence from $N_H \sim 10^{24}$ atoms cm^{-2} outside line of sight (e.g. molecular torus). Calculations based on Woźniak *et al.* (1998)
- No significant reflection component found $\Rightarrow$ N_H cannot be too large (c.f. RXTE)
- r ~ 0.1 pc i.e. away from AGN $\Rightarrow$ 4π thick disk covering model unlikely
- 4π covering model with distant Fe emitting region also unlikely (unification problems)

Summary

- Emission characterized by a heavily-absorbed power law
- Second power-law component necessary, consistent with VLBI jet
- Fluorescent lines from cold, neutral matter
- Fe Kα light curve consistent with no variability
- Molecular torus?